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Preliminary Evaluation of the Coastal Water off Delaware Bay for the Disposal of Industrial Wastes

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SUMMARY AND CONCLUSIONS

Increasing interest in the propriety of discharging industrial wastes at sea, on the part of industry and of the governmental agencies responsible for the control of pollution of inshore waters, has led to the present preliminary evaluation of the suitability of the area off the mouth of Delaware Bay for the disposal of waste materials.

The study has included a review of all available published data and unpublished data in the files at the Woods Hole Oceanographic Institution on the salinity and temperature of the waters of the Continental Shelf from Cape Cod to Cape Hatteras. In addition data obtained during recent studies of the area immediately off Delaware Bay, made for the Hydrographic Office of the U. S. Navy under the direction of Dr. Harold Haskin of Rutgers University, were kindly made available for the purpose of this report.

To supplement these hydrographic data a program of drift bottle releases was initiated to determine the rate, direction, and dispersal to be expected as a result of surface water movements in the area. About 3000 drift bottles were released in the area immediately off Delaware Bay with the co-operation of Dr. Harold Haskin. Drift bottle data, both published and from the files of the Woods Hole Oceanographic Institution, for this area have also been studied.

For the waters of the Continental Shelf between Cape Cod and Cape Hatteras we have estimated the average rate of the movement of the fresh water contributed by the various rivers between the immediate coastal area and the open sea. For an area in the offing of the Delaware Bay extending about 50 miles along the coast and about 40 miles offshore, the local currents and rates of exchange have been evaluated. The drift bottle studies have been concentrated in this same area, with some releases within the bay itself to determine the routes of escape of the estuarine water.

Summary of Results.

1. General Coastal Conditions:

The inshore circulation over the Continental Shelf is in a southwesterly direction generally paralleling the shore.

The entire mass of water over the Continental Shelf contains a volume of fresh water equivalent to 2 1/2 to 3 years contribution of the many rivers draining into the area. The larger values are obtained for summer accumulations, and reflect the large volume of river water contributed during spring runoff conditions.

The river water content of large areas ranges from values of about 6 to 9% near shore to values consistently less than 1% over the edge of the Continental Shelf.

2. Conditions off Delaware Bay.

Most of the freshened water issuing from the mouth of Delaware Bay turns southward along the coast of Delaware, where it occupies a band varying in width from 10-50 nautical miles. It is estimated that between 1/3 and 1/2 of the Delaware River water may escape northward.

The average time for the transport of Delaware River water through an area of almost 2000 square nautical miles lying immediately off the Delaware Capes is estimated to be two weeks to one month.

3. Drift Bottle Returns.

Recoveries of drift bottles decreased greatly with distance of the release point from shore. Of those released within 5 miles of shore 14.9% were recovered; of those released more than 20 miles from shore only 1.5% were recovered.

The velocities of drift confirm the current measurements and the average rate of circulation is estimated to be about 5 miles per day.

Most of the bottles recovered were found along the Delaware shore and to the southward. A few bottles released in the northern part of the area moved northward and were recovered along the coast of New Jersey. Only three of the bottles released offshore were recovered inside of Delaware Bay.

4. Delaware Bay.

The time required for the transport of Delaware River

water through Delaware Bay varies from 60 to 100 days and is related to river flow.

The dilution expected for a pollutant discharged within the bay and immediately outside the Capes is compared. The ultimate dilution obtainable with offshore disposal is shown to be about 20 times greater than the dilution obtainable within the bay.

About 27% of the bottles released within Delaware Bay were recovered. Half of these were recovered within the bay, and half escaped. All of the latter were recovered south of the entrance to the bay.

Conclusions

On the basis of all the facts available at present it appears that discharge of wastes is undesirable within 5 miles of the coast in any part of the area. Furthermore the circulation north of a line extending southeast from Overfalls Lightship is variable, and might permit the accumulation of wastes, and contamination of Delaware Bay by the influx of some of the contaminated water. Immediately south of this line, five miles or more from Overfalls Lightship, appears to be the most suitable location for the discharge of wastes. The drift of the water is less variable and the southward movement is more rapid than it is to the northward. The area is far enough offshore to avoid excessive contamination of the beaches. It is our opinion that this area could properly be used for disposal of materials of many kinds and in the quantities

to be anticipated at present.

This conclusion is based upon present knowledge of hydrographic conditions alone. The distribution of off-shore fishing should be considered and every effort made to avoid disposal near fishing grounds. Before discharge operations are initiated a detailed study of the local circulation in the proposed disposal area by release of drift bottles is recommended.

DISCUSSION OF THE PROBLEM

The problem of ameliorating the pollution load now carried by rivers and estuaries is a general one of wide application. These regions have been the site of great industrial development in recent decades, and the load of industrial and domestic pollution has, at times, exceeded the recovery capacity of the waterways. It may be anticipated that with the continued industrial growth of communities along the sea coast alternate means of disposal of wastes will have to be found.

For many years sewage sludges have been barged to sea from coastal cities and recently some industrial wastes have been so disposed of. A careful study has been made of the practice of discharging acid-iron waste from the titanium plant of The National Lead Company at sea in the offing of New York. The results of this study are summarized by Redfield and Walford (1951). One of the most important findings of the investigation was that the conditions in the estuary of the Raritan River, where the waste had been discharged previously, were considerably improved after the discharge at sea was adopted. The conditions of the offshore area, however, were not greatly affected since the same quantity of waste was reaching the area, though by a different route.

In evaluating the propriety of discharging wastes at sea the considerations must include the immediate effects

in the water behind the barge, the possibility of the accumulation of the wastes as a result of repeated discharge in the same area, and the direction in which the waste will be transported by the water currents and by wind drift. The character of the waste will determine the relative importance of the various criteria. In the wake of the barge, concentrations which would be innocuous for non-toxic wastes might cause serious damage to marine life if the waste contained toxic materials. Wastes which are in solution or in finely divided suspensions which settle slowly will be carried predominantly by the water currents. Floating wastes, on the other hand, will drift with the more variable wind patterns. This report is concerned with the probable fate of wastes in solution or in a suspension which settles very slowly so that wide dispersal is possible before the material settles to the bottom.

The local effects of the discharge of a waste containing sulfuric acid and iron sulfate has been described by Redfield and Walford (1951). Because of the turbulence caused by the passage of the barge, the waste was diluted, almost immediately with about 500 parts of sea water. Additional dilution occurred as a result of the normal turbulence of the sea, and the rate of this dilution was evaluated by Ketchum and Ford (1952).

The acid in the waste was neutralized rapidly by the excess base of sea water. Though acidities as great as pH 3

were observed immediately behind the barge, the acidity of the waste was neutralized within about 3 1/2 minutes. At any one time about three acres of the sea were made acid by the discharge of waste to a depth of not more than 50 feet, and the total area of the sea surface temporarily acidified by each load of waste was about 1/4 square mile..

The ferrous iron present in the waste colored the water in the wake of the barge a bright green. The iron was rapidly oxidized to ferric hydroxide, which formed a very fine precipitate which remained suspended for long periods of time. This suspension produced a red brown turbidity which was visible for three or four hours, and on one occasion a patch of water was recognizably discolored for about 8 hours. The amount of dissolved oxygen utilized in the oxidation of the ferrous to ferric iron was found to be negligible.

The waste was rapidly dispersed vertically, and reached depths of 50 feet almost immediately after the discharge. Though no effect of the waste on the bottom populations was detected following these disposal operations, the area for discharge should be as deep as possible to minimize the concentrations reaching the bottom populations.

Each waste should be tested for possible toxic effects on marine populations before discharge at sea. Toxicity tests made with The National Lead Company's waste indicated that zooplankton were temporarily immobilized, but considering the rapidity of dilution in the wake no permanent damage from the disposal operations could be expected. If the waste contains

toxic ingredients, even in fairly low concentrations, the effect on marine populations might be harmful.

Several advantages can be enumerated for direct discharge of waste at sea. The volume of water available for dilution of the pollutant is many times greater than the volume available in the tributary river. It is possible to select a discharge location which is much further from shore-based activities than is available within the confines of a river. The circulation of water in offshore areas is generally much greater, so that the waste material becomes widely dispersed. Associated with the ocean currents are vigorous mixing processes which increase the dilution effect.

The site for discharge of waste must be selected with a full knowledge of the oceanographic conditions in the area. It is apparent that fishing banks and grounds should be avoided at all costs. Not only are marine fisheries an important natural resource which should be protected, but also the fisherman, who is voluble in protecting his interests, may be alarmed by the operations even though it is possible to show that no deleterious effects of the discharge are to be expected. The necessity for avoiding bathing beaches is likewise obvious.

The currents which are one of the major advantages of the offshore area for discharge of waste materials could act as a disadvantage if they should flow in a direction which would bring the discharged waste toward popular fishing grounds or

beaches. It is necessary to know the character of the circulation in order to select the most suitable location for the discharge.

The most important current to avoid is the counter current of estuaries. The dynamics of the circulation in estuaries is such that a large flow of sea water is always drawn into the estuary where it is diluted with the river water and the mixture flows seaward by a different route. At times this counter current occupies the deeper part of the channel and may extend across the entire mouth of the estuary. In such cases the seaward flow of diluted water is restricted to the surface layers. At other times the counter current may extend from the surface to the bottom in one part of the mouth of the estuary, in which case the seaward flow of diluted water is horizontally separated from the counter current. Both of these conditions may exist for estuaries such as the Delaware Bay at different times of the year. For this reason it is important to know the seasonal variation in the circulation in order to determine whether different discharge sites will be necessary at different time of year.

In summary the following characteristics of a suitable site for the discharge of wastes at sea may be listed:

1. The site should be in a location where the seaward drift of estuarine water occurs and where the counter current of the estuary can be avoided.

2. It should have adequate depth of water so that the waste is widely dispersed or greatly diluted to avoid affecting the bottom population.

3. The area should be one of rapid circulation where the contaminated water is carried away completely and cumulative effects from successive discharges are eliminated.

4. The prevailing currents should not carry the wastes to fishing banks and beaches, before the natural processes of dispersion have reduced the concentration to negligible values.

The available data have made it possible to select a suitable site for the discharge of non-toxic soluble or suspended wastes in the offing of Delaware Bay. The circulation of water is rapid in this location, and the accumulation of waste as a result of repeated discharge should be at a minimum. The site is in deep water, and far enough from shore so that wide dispersal would be expected before any of the contaminated water approached the beach. The possibility of return of the waste to Delaware Bay from this site is considered negligible. Areas where the discharge of wastes would be undesirable are also defined.

GENERAL COASTAL CONDITIONS

For purposes of orientation it will be useful to discuss briefly the circulation and the salinity and temperature distributions of the water over the Continental Shelf between the region of Cape Cod and Cape Hatteras. This area forms an oceanographic unit which is almost completely isolated from the adjacent coastal waters. Delaware Bay opens near its geographical center. The Continental Shelf extends seaward to the 100 fathom depth contour and the waters on the Continental Shelf are isolated from those of the open ocean by the Gulf Stream. Between the edge of the Shelf and the Gulf Stream is found the slope water which is different from either the coastal or Gulf Stream waters.

The coastal circulation

Along this entire coastline there is a westward and southward drift of the inshore waters extending south to Cape Hatteras where the Gulf Stream is close to the coast. There the general southward drift of inshore water is apparently diverted and turned abruptly to the northeast. The water over the outer part of the Continental Shelf has a northward and eastward drift which may be initiated by the abrupt transition at Cape Hatteras. There is no clearly marked boundary between the inshore and offshore drifts, and, indeed, it is not yet known whether the two drifts comprise one large eddy extending over the length of the entire area, or several smaller ones.

Several thousand drift bottles have been released in recent years in the Continental Shelf area between Cape Cod and Cape Hatteras. Redfield and Walford (1951) have presented the results obtained from the release of more than 2000 bottles in the offing of the Hudson River, and Miller (1952) has summarized the results of releases in May 1951 over the entire area.

These drift bottle data confirm the general pattern of circulation outlined above. Miller shows that practically all of his recoveries were from south of the point of release. Only two of the drift bottles released north of Cape Hatteras were recovered from south of Cape Hatteras, confirming the abrupt reversal of the inshore drift in this region. Redfield and Walford found about 40% of their recoveries were north of the point of release, along the Long Island shore. Most of these had been released within five or ten miles of the shoreline during periods of prevailing southwesterly winds.

The percentage returns were high (75-80%) from many areas within five or ten miles of the coast, but the proportion of bottles returned decreased rapidly with increasing distance of the release point from the coast. Few bottles released more than 20 miles from shore were recovered on the beach. Immediately south and east of the entrance to Delaware Bay, Miller (1952, Figure 8) shows a large area from which no returns were obtained. A more intensive drift bottle survey of this area has been made for the purposes of this investigation,

and the results will be discussed below.

The highest concentration of recoveries was found along the coast of North Carolina, about 50 miles north of Cape Hatteras (36°N to 36°20'N). Bottles released in nearly all parts of the Continental Shelf came ashore on this short length of beach. (See: Miller, 1952, Figure 15) In this neighborhood the coastline turns slightly eastward. This, and the complicated circulation which results from the proximity of the Gulf Stream, and the reversal of the southward inshore drift in this region apparently make this stretch of coast particularly subject to the beaching of floating objects.

Distribution of salinity and temperature

The coastal waters are characterized by the fact that they are measurably diluted by the river inflow along the entire coast and by the fact that the surface temperature undergoes a marked seasonal variation. Bigelow (1933) has described the cycle of temperature and Bigelow and Sears (1935) the salinity of this area of the Continental Shelf. These two reports describe in detail both the seasonal and geographical variations in temperature and salinity to be expected in the area. Miller (1952) presents in greater detail the surface salinity and temperature distribution observed in May 1951.

In general the salinity increases from values of 32.0 parts per thousand ($^{o}/_{oo}$) or less near the coast to values of 34.0 - 35.0$^{o}/_{oo}$ near the edge of the Continental Shelf.

Water of $35.0^{o}/oo$ or slightly more is normally found at variable depths at the edge of the Continental Shelf. The water is most saline during the winter. There is a rapid freshening of the inshore water during the spring, a process which may not culminate before mid-summer, when the average salinities are at their lowest. During and following the summer the inshore belt of greatly freshened surface water is broken into isolated pools. In summer both the reduced salinity and the increased temperature of the surface water result in a high degree of vertical stability. At the onset of fall, with the cooling of the surface layers, this stability is decreased and greater mixing with deeper waters is possible. The vertical range of salinity is decreased as the surface salinity increases because of the more active mixing. There is thus a major change in the coastal water from the summer conditions of vertical stratification with fresher, warmer water at the surface, to a winter condition approaching vertical homogeneity, with little difference of salinity or temperature from top to bottom.

Opposite the mouth of each of the major estuaries, the additional river effluent produces rather complicated changes in the generalized picture. The effects of the Hudson River, the Delaware River, and Chesapeake Bay are as yet rather incompletely known but extensive studies are now being made of each. In all cases the low salinity water entering the sea from the estuary has tendency to turn to the right and flow southward

along the coast as it leaves the mouth of the estuary. This is the result of the rotation of the earth. The tendency is augmented by and may in turn augment the inshore drift.

In spite of this general tendency of the waters of the estuary to flow southward along the coast, various other forces may act to modify the circulation in greater or lesser degree. Thus it was found off New York (Ketchum, Redfield and Ayers, 1951) that when the river flow was large and the temperature of the surface water relatively high, there was an increased tendency for the Hudson effluent to spread widely over the surface in a diffuse pattern. When the river flow was smaller and the surface water temperature was not greatly different from that of the offshore waters the flow was confined most closely to the coast. During periods of very low river flow the patterns of distribution were erratic, changeable and unpredictable. Although the general forces involved in determining the type of circulation patterns could be recognized, it was not possible to predict what the result would be when these forces were in opposition.

CONDITIONS OFF DELAWARE BAY

Delaware River Flow

The pattern and the rate of the circulation of water off the mouth of estuaries is dependent upon the volume of fresh water entering the sea from the tributary rivers. The pattern of the circulation can be evaluated by using the fresh water as a tracer of water movements, and the rate of the circulation can be determined by comparing the quantity of fresh water accumulated with the rate at which it is supplied. River flow is thus of great value in the interpretation of the distribution of the properties off the mouth of the estuary.

The Delaware River flow at Trenton for the period January 1951 to July 1952 is given in Figure 1. The flow at Trenton is not directly applicable to the offshore area, however, since the river and bay receives fresh water from sources further downstream, and considerable time is required for the transport through the estuary of the water introduced at Trenton. The downstream additions to the Delaware River flow at Trenton have been evaluated on the basis of drainage areas and gaged river flows. The data necessary are presented in Table I which shows that the total drainage area above the Capes is about twice as large as the drainage area above Trenton. The stream flow of about 69% of the entire drainage area is gaged. By assuming that the ungaged areas have the average flow per square mile characteristic of the gaged area, it is computed that the total volume of river water tributary

to the Delaware at the mouth of the estuary is 1.94 times the flow at Trenton. For practical purposes the river flow at Trenton can be doubled to obtain the rate of addition of fresh water to the sea between the Capes.

The time required for the transport of fresh water through the Delaware Bay system (flushing time) is variable and related to river flow (see Ketchum, 1952). For periods of low rates of flow (0.5 billion ft^3/day) the flushing time may be almost four months, for high rates of flow (2.0 billion ft^3/day) it is reduced to about two months. For the mean rate of flow (about 1.0 billion ft^3/day) this time is about 100 days.

Salinity distributions

During 1951 and 1952 the distribution of salinity in the offing of Delaware Bay has been observed at six periods. One cruise in May 1951 was made on the ALBATROSS III by Arthur R. Miller of the Woods Hole Oceanographic Institution. Observations have also been made by Dr. Harold Haskin of Rutgers University for the Hydrographic Office of the U. S. Navy Department. His results are presented for five periods, August - September 1951, October - November 1951, February - March 1952, May 1952 and July 1952. The co-operation of Dr. Haskin and of the Hydrographic Office in making these results available is greatly appreciated.

The surface distributions of salinity observed during these surveys are given in Figures 2 - 7. All of the

salinity distribution patterns have some common properties. In all cases the freshened water issuing from the mouth of Delaware Bay turns southward and is found in a band along the Delaware coast. The contours identifying water of high salinity offshore lie nearly parallel to the coast, or in some cases to the underlying bottom topography. The actual salinity, however, undergoes marked fluctuation during the year.

The lowest salinities were observed during the February - March survey. At this time water of salinity 29.0‰ was found along the entire Delaware coast, and opposite Cape Henlopen the salinity was 25.0‰. For the three months prior to this cruise the river drainage had been about double the mean value -- ranging from 19,700 to 23,700 cfs. at Trenton. Within about fifteen miles from the shore the salinity increased to 33.0‰, showing that the freshened water was closely confined to the coast. The water fresher than that north of Cape May was restricted to a band extending ten miles or less from the coast.

In May, 1952 water of 29.0‰ salinity also extended well beyond the mouth of the bay. This survey was also preceded by exceptionally high Delaware River flows at Trenton, being 23,500 cfs. in March and 35,000 cfs, in April. The pattern of distribution was, however, quite different from that observed in February and March. In May the 32.0‰ salinity water was fifty miles from the

coast and no surface water in the surveyed area had salinities as great as $33.0^{o}/_{oo}$. At this time the freshened water extended seaward for great distances, rather than being confined closely to the coast. This spreading of the diluted surface water is related to its lower density which is determined both by the temperature and by the salinity of the water. By May the vernal warming of the water was well advanced and the surface temperatures ranged from 55° - 57°F. over the area.

The widespread distribution of low salinity water appears to persist throughout the summer, since the July 1952 and the August - September 1951 surveys also detected low salinity water many miles from shore. During the former period salinities less than $30.5^{o}/_{oo}$ were widespread. This survey was made at the end of a rapidly decreasing river flow, but even in July 1952 the flow was greater than the long period mean. The August - September 1951 cruise, was made after a long dry period when the flows had been about 8,000 cfs. or less at Trenton for a period of four months. Practically all the water within 35 miles of shore still had salinities less than $32.0^{o}/_{oo}$. Reflecting the low river flow, these salinities were about $1.0^{o}/_{oo}$ higher than during July 1952. The surface temperatures were fairly high during both periods, ranging from 72° - 79°F. in August, 1951, and from 75° - 80°F. in July, 1952.

The river flow had been low for six months when the

October - November 1951 survey was started. The water was considerably more saline at this time than two months before. Water less than 32.0‰ was restricted to a band extending about ten miles from the Delaware shore, in contrast to the 35 mile band observed in the previous August - September survey.

The variations in distribution patterns discussed above are similar to those described by Ketchum, Redfield and Ayers (1951) for the New York Bight. The freshened water as it flows into the sea has tendency to turn to the right because of the rotation of the earth. The extent to which it spreads over the surface is determined by its density relative to that of the invaded sea water. The density is, of course, a function of both salinity and temperature. The dilute, warm water of spring and summer has a greater tendency to spread seaward than the dilute, cold water of mid-winter. Thus in February, in spite of large river flows, the cold, diluted water was closely confined to the coast whereas in summer, though the river flow was less, the freshened water spread more widely. When the river flow was great Ketchum, Redfield and Ayers (1951) were able to explain the distributions observed in the New York Bight from consideration of the basic oceanographic and meteorologic factors involved. On two surveys, made following low river flow periods, however, the distri-

bution patterns were erratic, changeable and unpredictable. The data available for the offing of Delaware Bay are not sufficient to apply similar methods of interpretation, but qualitatively, at least, it appears that similar conclusions are justified.

These observations on the distribution of salinity are necessary for the evaluation of sites suitable for the discharge of wastes at sea. The drift of water will carry the wastes southward and if the wastes are discharged south of Cape Henlopen it seems unlikely that any will be returned to Delaware Bay. During the spring and summer months, when the freshened water is spread widely to the eastward, the drift must have eastward components to produce the observed distributions. At the time when beaches are most used, therefore, the waste will be transported further offshore. The variations in the patterns of distribution can not be attributed solely to the season of the year, however, since they depend in part upon fluctuating river flow. It does not seem practical, therefore, to suggest separate sites for winter and summer disposal of wastes.

RATE OF CIRCULATION

The rate of circulation can be evaluated from the distribution of salinity and the river flow. The basic assumption is that the observed distribution of salinity is in a steady state. Under these conditions, a volume of fresh water equal to that introduced by the river in a given interval of time must be transported seaward through the area or through any complete cross section in the same interval of time.

The fraction of fresh water (F) in any given sample is given by:

$$F = \frac{S_b - S}{S_b} \qquad (1)$$

in which S_b is the base salinity of the sea water which is mixing with the river effluent and S is the salinity of the sample. The accuracy of this computation obviously depends upon the selection of the proper base salinity. In some localities this is a reasonably definite quantity since the mixing sea water can be readily identified from the plots of the distribution of salinity. In the offing of Delaware Bay there is considerable uncertainty in the definition of the mixing sea water. This will be discussed below.

The flushing time has been defined as the average length of time required for the river water to move through an area. From the fraction of fresh water in various samples

the total quantity of river water accumulated in the area considered is computed. The flushing time (T) is then given by:

$$T = \frac{Q}{R} \qquad (2)$$

in which Q is the total volume of river water accumulated, and R is the rate of river flow.

The non-tidal drift (NTD) of the water is the rate of flow necessary to transport the river water seaward through any complete cross section. The computation is as follows:

$$NTD = \frac{R}{FA} \qquad (3)$$

in which F is the average fraction of fresh water in the cross section and A is the total area of the cross section.

Computations of the flushing time and non-tidal drift have been made for the Continental Shelf between Cape Cod and Cape Hatteras, and for an area of about 2,000 square miles off the entrance to Delaware Bay.

The Continental Shelf

The amount of river water accumulated over the Continental Shelf between Cape Cod and Cape Hatteras has been evaluated in order to permit the estimation of the flushing time. The flushing times obtained in this way are averages over wide areas. The specific conditions off the mouth of the Delaware will be discussed below.

Observations of salinity at various depths made at

856 hydrographic stations have been evaluated in order to determine the total quantity of river water in the area. Off the edge of the Continental Shelf the salinity of the deeper water approaches a constant value of about 35.0$^{0}/_{00}$. This may be taken as the base salinity, characterizing the ocean water which is diluted over the Continental Shelf by river drainage (S_b in equation 1).

The data available make it possible to compute the total quantity of fresh water for three periods during the year, namely: 1) April, May and June; 2) July, August, and September; 3) October through March inclusive. The Continental Shelf area was divided into six regions which are shown in Figure 8. For each of these regions the fractions and volume of fresh water between various depth contours has been estimated. The results of these calculations are given in Tables II, III and IV. The total quantities of fresh water between various depth boundaries at the three times are summarized and presented in Table V.

As would be expected the proportion of fresh water decreases with distance from shore. Within the 20 fathom contour the fraction of fresh water ranges from about 6 to 9% of the total volume. In the water lying offshore between the 100 and 1000 fathom depth contour, the proportion of fresh water is less than 1%. In these deeper areas, of course, most of the fresh water is found in the surface layers. In general the fraction of fresh water also decreases in a more or less regular way from the northern-

most to the southernmost areas. Near the shore the proportional decrease is small, but outside of the 50 fathom depth contour it becomes quite marked at some seasons of the year.

The total volumes of river water accumulated in the spring and in the fall and winter seasons are about equal. The volume of river water found during the summer season is some 25% greater than that present in the other two periods. This no doubt reflects the delayed effect of the greatly increased spring inflow of water from the rivers.

The interpretation of these data depends upon assessing the rate of contribution of river water to the area by the various rivers and drainage basins. We have estimated the drainage area of the various rivers which lead directly into this area as 116,000 square miles or 325×10^{10} square feet. The average precipitation over this area is 3.54 feet per year.

For about 68% of the drainage area listed above, data are available indicating the river flow. For the gaged drainage areas the river flow corresponds to 32.8% of the rainfall. Assuming that this same proportion applies for the entire area, the contribution of fresh water to the sea from the rivers is 378×10^{10} cubic feet per year or 10.4×10^{9} cubic feet per day.

The ratio between the quantity of river water accumulated within the area and the daily increment from the

rivers has been defined as the flushing time. The flushing times calculated from these data are 2.32 years for the spring accumulation, 2.26 years for the fall and winter accumulation and 2.89 years for the summer accumulation.

These data indicate that the fresh water present over the Continental Shelf increases between spring and summer by a volume equivalent to about one half of the total annual contribution of the rivers, and decreases again by an equal amount between the summer and the fall and winter observations. More than half of the mean annual river contributions can be expected during the months of March, April and May (Bigelow, 1935). The increase in fresh water observed in the summer can probably be attributed to the delayed action of these large spring river flows. During the summer, rainfall and river flow are at minimum values, and evaporation is greatest during the fall and early winter. The decrease in volume of accumulated fresh water between the summer conditions and the fall and winter conditions can probably be attributed to these processes acting in addition to the normal exchange of fresh water by mixing with ocean water.

The Offing of Delaware Bay

As mentioned above it has proved difficult to assign, with any assurance, a value to the base salinity for the water in the offing of Delaware Bay. A review of the distribution patterns (Figure 2 - 7) shows that the surface

salinity in all parts of the area undergoes marked variations throughout the year. There is no clear demarcation at any time between undiluted water and the water diluted with Delaware River effluent. The greatly diluted water is readily identifiable, but the boundary between a small amount of dilution and no dilution at all is very indistinct. From tidal current observations it is known that the non-tidal drift in this part of the Continental Shelf is generally southward. Current measurements made by the U. S. Coast and Geodetic Survey presented by Zeskind and Le Lacheur, (1926) indicate that the non-tidal current at Overfalls Lightship flows south 17° east at a rate of 2.88 nautical miles per day (17,500 ft/day) and at Five Fathom Bank Lightship, about 20 miles east of the entrance, it flows south 75° east at 2.54 nautical miles per day (15,400 ft/day). The water to the north of the entrance is, thus, the only source of <u>surface</u> water which might be expected to enter Delaware Bay. A few drift bottles liberated in the northern part of the area have been recovered within the bay. However, the distribution patterns show that this water merges almost imperceptibly with that to the south of the entrance so that no clear source is indicated. It seems probable that the deeper water off the entrance to Delaware Bay may contribute a substantial part of the sea water within the bay, but the data are not definite enough to define the source clearly.

The above mentioned difficulties make the selection of a base salinity somewhat arbitrary. The foregoing discussion of the distribution of fresh water on the Continental Shelf between Cape Cod and Cape Hatteras indicates that one may expect, on the average, about 7% fresh water in the mixture found within the 20 fathom depth contour at all times of the year. For analyzing the distribution of Delaware River water, we have, therefore, used a base salinity of $32.5^{o}/_{oo}$, which corresponds to an admixture of 7.15% river water from other sources with pure oceanic sea water of a salinity of $35.0^{o}/_{oo}$. Water of this salinity was always found at some depth within a radius of 10 miles off the entrance of Delaware Bay.

Non-tidal drifts: Adequate salinity data at all depths are available to analyze for the non-tidal drifts and flushing times during the October - November 1951 cruise and the February - March 1952 cruise. The location of the cross sections and the enclosed areas which have been used in the analysis are shown in Figure 9. For the October - November cruise 1951 the areas of the cross sections and the associated transport data are presented in Table VI. The river flow applicable at this time was 1.08×10^{9} cubic feet/day. The non-tidal drift computed for the innermost section was 4640 feet/day. This is considerably less than the 15000 to 17000 feet/day drift obtained from direct current measurements. This result suggests that our estimates of the accumulated fresh water are too high and that perhaps a lower base salinity could

have been selected. More important, however, it indicates that our evaluation is conservative, and that the rate of circulation may be as much as double the rate estimated here.

This calculation suggests that about 26% of the water entering the sea between the Capes escapes northward, about 28% escapes to the east and the remaining 46% moves southward through the innermost cross section. In the next seaward section the data indicate that an additional 20% of the original inflow escapes to the north. Practically all of the remainder moves in a southerly direction. This southerly drift is maintained in all of the outer cross sections. Throughout the area the average non-tidal drift estimated for the various cross sections range from 3290 - 9350 feet/day.

The analysis of the February - March distribution pattern gives non-tidal drifts which are more nearly like those obtained from direct current measurements, although they are still somewhat smaller. The results are given in Table VII. For this survey it was possible to analyze the transport through a smaller section immediately outside the Capes. In this case 83% of the total river discharge moved southward, 17% to the east. From the second cross section about 3.5% of the water moved to the north and 79% moved south, the remainder moved east. The third section contains a longer northern boundary and 33% of the Delaware River

flow escaped northward through this section. All of the remaining river water, constituting 63.5% of the total flow, moved southward through this, and the remaining two cross sections. The actual velocities of non-tidal drift determined for the February - March salinity distribution range from 9150 ft/day to 14350 ft/day.

The analysis of both surveys indicates that a considerable proportion (36.6 - 47.7%) of the Delaware River effluent escapes to the northward. There is no method for determining what proportion of this re-enters the area considered. This phenomenon explains, in part, the difficulty of assigning with assurance the base salinity for these calculations since the water to the north already contains some Delaware River water.

Flushing time: From the same salinity data the flushing time of the various areas shown in Figure 9 can be computed. This has also been done for the October - November 1951 and February - March 1952 surveys. The results are presented in Tables VIII and IX. During the October - November survey freshened water was found to extend over a sea surface area of 1920 square nautical miles. The total volume of fresh water admixed with sea water in this area was 38.39×10^9 cubic feet. Using a river flow of 1.08×10^9 cubic feet/day, this corresponds to an average flushing time of 35.54 days. During the February - March survey freshened water was found in an area of 1805 square miles. The volume

of fresh water accumulated at this time was 43.16×10^9 cubic feet. The river flow applicable at this time was 2.67×10^9 cubic feet/day giving a flushing time for this period of about 16.17 days.

It will be remembered that our estimates of volumes of fresh water accumulated in this area are probably too large as evidenced by the fact that the non-tidal drifts calculated were smaller than measured non-tidal currents. The data on the non-tidal drifts suggested that the February - March survey was more nearly correct than the October - November survey. If too high a base salinity has been chosen for these calculations, the flushing times estimated in the previous paragraph are likewise too long. Thus, the estimate of two weeks to a month for the flushing time for an area of nearly 2000 square nautical miles outside the Delaware Capes is probably conservative.

It may be mentioned that because of the large apparent errors in the non-tidal drifts for the October - November survey, comparable calculations have been made assigning the value of $32.0^{o}/_{oo}$ for the salinity of the mixing sea water. This would correspond to about 8.6% fresh water mixed with oceanic sea water of salinity $35.0^{o}/_{oo}$. This calculation gave non-tidal drifts near the mouth of the bay of about 14,000 ft. per day, a value which compares well with the measured non-tidal drifts. The drifts, however, increase to the southward to impossibly large values. This may be an

indication that the October - November survey was made during a time when the salinity distribution was not in steady state and that different criteria for the northern and southern parts of the area might be necessary. It is mentioned here, however, since the total accumulation of river water based upon the salinity value of 32.0$^{o}/_{oo}$ was 15.81 x 10^9 cubic feet, corresponding to a flushing time of 14.6 days. If different salinities are used for the two cruises, therefore, it is possible to obtain virtually identical flushing times for the two periods. This is of interest since our study of the New York Bight (Ketchum, Redfield, and Ayers, 1951) indicated that the flushing time remained constant even though the river flow varied by a factor of five. More complete data were available for the New York Bight, and the base salinity could be determined with more certainty.

In spite of the uncertainites of these calculations, they do indicate that the area in the offing of Delaware Bay flushes rapidly and it should, therefore, be an advantageous location for the dispersal and dilution of introduced pollutants.

DRIFT BOTTLE RETURNS

Data obtained from the recovery of drift bottles provide positive information on the probability that floating pollutants released in any area will reach adjacent shores. They consequently give valuable information on the probable transport of such pollutants as oil, garbage, and the floating solids derived from domestic sewage which may contaminate the water and find their way to beaches.

Drift bottles also supply useful information on the general character of the circulation of the surface water of the sea. However, since the surface of the sea is exposed directly to the action of the wind, and its motions do not necessarily coincide with the mass movement of the underlying water, the results cannot be applied with equal assurance to soluble or suspended pollutants which may be present at greater depths. Moreover, such pollutants become diluted rapidly in the course of their drift and might become innocuous even though a drifting object is carried in the water to a distant shore. For these reasons drift bottle data must be interpreted with care.

Industrial wastes such as acid iron sulfate frequently discolor the waters into which they are discharged and the discoloration may cause alarm to the public, irrespective of any harm which may result. Drift bottle data supplies

pertinent information on the directions and rates at which such visible effects may spread.

Data

Data are available from the systematic release of 1,740 bottles at 145 stations along the coast between Cape Cod and Cape Hatteras in May 1951. These data, which have been analyzed by Miller (1952) in the appended report, provide a background on the general character of the drift of the coastal water. For a detailed study of the surface drift in the offing of Delaware Bay the data from 45 stations distributed from Barnegat Lightship to Chincoteague Inlet have been combined with additional data on bottles released through the courtesy of the U. S. Hydrographic Office and Dr. H. H. Haskin of Rutgers University. Table X summarizes the numbers of releases and returns available for this study.

Theory for interpreting drift bottle statistics

In order to interpret the statistics of drift bottle returns, it may be assumed that the motion of the drift may be resolved into two components:

1) A motion parallel to the shore due to the net drift of the coastal water as a whole along the coast;

2) Random scattering in every direction due to eddy motion occasioned by the shearing forces due to tidal motion, wind, or any other cause.

A group of bottles released at any position may be expected to drift in such a way that the mean position of the group will move according to the first component. The individual bottles will scatter from this mean position so that the group as a whole will occupy an ever-increasing circular area surrounding the mean position. It follows that along a continuous coast line at least half the bottles will scatter seaward and never reach the shore. If the coast line from which returns may be expected is limited in extend, it will follow that those bottles which depart least from a course parallel to the shore will not beach before leaving the limits of this coast, even though their random movements carry them landward. Consequently, an increased number of bottles will fail to reach the beach. This number will become larger as the distance from shore at which the bottles are released increases, and there will be a distance beyond which no bottles will be beached because they will be carried beyond the limits of the recovery shore before random scattering brings them to the beach.

Effect of distance of release from shore

Along the North Atlantic coast the southwest drift of the coastal water is terminated sharply at Cape Hatteras where the current meets the Gulf Stream which turns it offshore. The shore line from which the

bottles released off Delaware Bay may be returned extends consequently for an average distance of only 200 miles. The conditions are consequently fulfilled that the number of returns should diminish with the distance from shore at which the bottles are released. Table XI shows the number of bottles released at various distances from shore along the coast between Barnegat Light and Chincoteague Inlet and the per cent returns reported. It indicates that the chance of a drifting bottle reaching shore is small if it is released more than five miles from the beach and that practically no returns are obtained from bottles released twenty miles from shore. When it is realized that a bottle released at this distance must deviate from a course parallel to the shore by an angle of only 3°, it is evident that the tendency for bottles to scatter by random movements is very small indeed. This is further supported by the tendency of bottles released at the same time and place to "beach" near together even after drifts of more than 100 miles.

A more exact indication of the tendency of the bottles to scatter at random is given by estimating the apparent angle of departure from a course parallel to the shore. This angle may be defined as $\sin^{-1} a/b$, where a is the distance of release from shore and b is the distance drifted to the point of recovery. Table XII gives the number of bottles recovered with various angles of departure. Note that practically half

the bottles appear to have departed by less than 10° from a course parallel to the shore when they beached. Only 11 per cent have moved against the southwesterly drift of the coastal circulation -- as indicated by angles of departure greater than 90°. This upstream drift is associated with a localized area off the southern New Jersey coast to be discussed below.

An examination of detailed charts showing the points of release and recovery indicates that the returns close to the point of release are associated with bottles released near shore and that the farther from shore the release the greater the distance southward traveled before beaching. This observation confirms the conclusion that random motion causes relatively small departures from the course parallel to shore which arises from the general southwesterly coastal current. The practical importance of these conclusions is that great advantage is to be obtained in disposing of wastes by operating at a reasonable distance from shore, since the affected mass of water will not spread shoreward rapidly and will be carried a great distance before affecting the water along the beaches.

Rate of Drift

From the distance between the points of release and recovery of a drift bottle and the time elapsing between its release and its reported recovery an estimate may be made of the minimal rate of its drift. How much faster it

traveled cannot be determined because many bottles are not found until long after they have come ashore. Others may be caught in localized eddies and thus follow circuitous routes to their point of recovery. For these reasons the statistics bearing on the rate of drift of bottles is heavily weighted in favor of rates slower than the true average drift.

Examination of 193 returns from bottles which beached to the southwest of the point of releases gave the following distribution of minimal rate of drift.

More than 10 miles per day	-	3 percent
More than 6 miles per day	-	10 percent
More than 3 miles per day	-	33 percent
More than 2 miles per day	-	50 percent
More than 1 mile per day	-	77 percent

In evaluating these data there is no sound method of allowing for time elapsed before the beached bottles are discovered. However, this error will in general be least if the distance drifted is relatively long and thus requires substantial time. In many cases a number of bottles released at the same point were found so close together, after drifting long distances, that it is probable that they moved in company. In such cases the first arrivals agreed closely in their time of arrival and in the resulting minimal rates of drift and were presumably all recovered shortly after beaching. The later arrivals varied greatly in time of recovery and presumably

were beached in inconspicuous places which delayed their discovery. For example the following returns resulted from a set of 12 bottles released 12 miles off Atlantic City, New Jersey which beached near the mouth of Chesapeake Bay.

Distance Drifted miles	Elapsed Time days	Minimum Rate miles per day
170	43	4.0
173	45	3.8
170	52	3.3
186	87	2.1
160	115	1.4
187	163	1.2
167	266	0.6

In such a case it seems probable that the drift was at a rate close to 4 miles per day.

The examination of similar cases where multiple returns were obtained from simultaneous releases after relatively long drifts indicated that the drifts of the first bottle recovered were accomplished at minimum rates of 3 to 6 miles per day. This corresponds with the rates estimated by Miller (1952) of 4 to 6 miles per day for the region off Delaware Bay. There is positive evidence that in exceptional cases the bottles may drift at rates up to 13 miles per day.

In view of these observations 5 miles a day appears to be a reasonable estimate of the average velocity of the coastal current off Delaware Bay.

Details of circulation

The preceding section gives a statistical picture of the movements of the surface waters along the shores of southern New Jersey and Delaware. An examination of individual drift bottle returns shows that there are some localized peculiarities of the circulation immediately off Delaware Bay which are not brought out by statistical treatment.

Over a large area covering the northern and eastern approaches to Delaware Bay the direction of drift is variable and uncertain, many bottles moving northward to beach between Cape May and Atlantic City, while others are recovered to the south. Over the approach from the south to southeast, the direction of drift is almost uniformly in a southerly direction, only two recoveries from one station being the exception.

Figure 10 shows positions at each of which sets of twelve drift bottles were released during July 1952. Arrows indicate the direction to the point where the bottles were recovered. Positions from which some bottles moved northward are distinguished by solid circles. From each of the two stations marked B one bottle was recovered inside Delaware Bay.

These data are interpreted to indicate that the principal drift of water escaping from Delaware Bay lies along the Delaware shore, where it intensifies the general southerly movement of the coastal water. In the bight lying north of

this stream, countercurrents tend to form which carry water northward in an eddy along the southern New Jersey coast. This region is probably the source from which salt water is drawn into Delaware Bay by tidal action as required to produce the existing salinities of the bay water. It coincides in position with the shoal area lying to the northeast of the submerged gorge which forms the deep-water approach to Delaware Bay.

The extent of the eddy revealed by the drift bottles released in July 1952 appears to be variable. In May 1951, twenty-three of the bottles released in this area were recovered. All were transported southward. In February - March 1952 and May 1952, a substantial number of bottles were recovered to the northward but these came from a more restricted area, lying closer to the New Jersey coast.

In the discussion of the drift bottles released in Delaware Bay, to follow, it is pointed out that about half of the bottles recovered were found outside the bay. These recoveries came without exception from south of Cape Henlopen. This observation is interpreted to mean that the principal escape of Delaware Bay water is along the Delaware side and that little escaping water enters the offshore area from which bottles are frequently carried northward to beach in New Jersey.

DELAWARE BAY

Flushing times and diluting volumes

The distribution of salinity in the estuary of the Delaware River has been discussed by Ketchum (1952). It was concluded that the volume of fresh water accumulated in the bay, and the flushing times were both dependent upon the rate of river flow. For low rates of flow (0.5×10^9 ft^3/day) the flushing time from Trenton to the Capes was estimated at almost four months. For flows near the annual mean value ($1.0 \times 10^9 ft^3$/day) the flushing time was about 100 days, and for river flows about double the mean value flushing times of about 60 days were obtained.

These times represent not only the accumulation of river water, but also the accumulation to be expected for pollutants introduced in the upper end of the estuary. For the part of the estuary below Wilmington, Delaware, the longest times given above would be reduced by about 30 days, and the shortest times by about ten days. Even the lower part of the estuary could thus be expected to accumulate between 50 and 90 days contribution of a waste material discharged into the estuary at Wilmington.

A dilution factor can be calculated for the purpose of comparing discharge into the estuary at Wilmington, and discharge offshore. Within the estuary 50 - 90 days pollution would accumulate in a volume of $486 \times 10^9 ft^3$. Each days pollution would thus be diluted, on the average, by

5.4 to 9.8 billion cubic feet of water. In the offshore area the ultimate dilution expected can be obtained by the ratio of the total volume of water to the flushing times listed in Tables VIII and IX. Each day's pollution would be diluted by 171 to 368 billion cubic feet of water. Furthermore, 50 to 90 days are required to achieve this average dilution within the bay, whereas the much greater dilution offshore would be achieved in 16 to 35 days.

The above dilution figures are averages over large areas. For smaller parts of the system the volume available for dilution can be estimated from the distribution of fresh water. In order to transport a given volume of river water seaward, the total volume of mixed water moving seaward must increase as the proportion of sea water in the mixture increases. This total volume has been called the escaping volume (E) and is given by:

$$E = \frac{R}{F} \tag{4}$$

in which R is the river flow and F is the mean fraction of fresh water in the mixture.

The escaping volume, which is the volume available for the dilution of the amount of pollution added each day, is presented for various locations in Table XIII. At Wilmington this volume ranges from 0.8 x $10^9 ft^3$/day for low rates of river flow to 2.9 x $10^9 ft^3$/day for high river flows. At the Cape this volume ranges from about 15 - 25 x $10^9 ft^3$/day.

This emphasizes the advantage of discharge in the open sea, since immediately outside the Capes the available diluting volume is about double the best obtainable within the bay.

Drift Bottle Returns

Drift bottles have been released at stations within Delaware Bay as shown in Table XIV. The positions of release were arranged in lines extending across the bay spaced from the Capes to the narrowing of the river at Ship John Light. The number of returns was exceptionally large, being 27 per cent. Of these, one half escaped from the bay and were returned from the outer coast. Most of these bottles came ashore on the coasts of Delaware and Maryland, only three beaching south of Chesapeake Bay. Their behavior was similar to that of bottles released close to the outer coast and thus indicates that the outflow from the bay remains close to the coast.

Of the bottles recovered from the shores of Delaware Bay, none beached on the eastern shore, and only four moved up the bay before beaching. Twenty bottles released in the eastern half of the bay moved across the bay to beach on the Delaware shore. Bottles released in the western half of the bay tended to move southward for some distance before beaching. As a result 80 per cent of the recoveries within the bay were from the southern half of the Delaware shore; i.e., south of 39°N. latitude.

These observations indicate that there is a substantial dirft seaward of the surface waters of Delaware Bay and that it is strongest on the western side of the bay. They also show that there is a definite set of the water movement across the bay in a westerly direction. The results are also consistent with the view that the net movement of water along the eastern side is northward and that bottles released in this side escape by taking a circuitous course up and across the bay before moving seaward in the drift down the Delaware shore.

The data on the longest and fastest passages of drift bottles are of interest in showing the general rate of movement of the drift down the bay. The fastest drift recorded is from a bottle which moved from the river mouth southward for a distance of thirty-three miles in not more than five days, or at a minimum rate of 6.6 miles per day. A number of other bottles made long drifts at rates from two to four miles per day. These drifts all originated in the northwest quarter of the bay. In contrast none of the returns from the northeast quarter gave rates greater than one mile per day, indicating a more sluggish circulation or, more probably, the longer course taken by such bottles before reaching the Delaware shore.

In contrast to the large percentage of drift bottles which drift out of Delaware Bay before recovery on the coast, only four bottles released offshore have been recovered within

the bay. Two of these originated in the area of variable motion lying in the northeastern approach to the bay and are shown in Figure 10. One released in May 1951 originated far to the north of the Delaware Bay area and presumably entered over a similar course. One released in May 1952 immediately outside Cape Henlopen was recovered from the beach at Lewes, Delaware, which it had probably reached on a single inflowing tide. These few records indicate how strongly the water sets out of Delaware Bay and how unlikely it is that pollutants discharged into the offshore waters will be introduced into the bay by tidal exchange.

RECOMMENDATIONS ON WASTE DISPOSAL

Operation of the barge.

The following suggestions are made concerning the operation of the barge, though more specific details concerning the character of the waste, the volume and frequency of disposal should be available before they can be considered final.

The waste should be discharged under the surface of the water in the wake of a moving barge to take advantage of the initial mixing which results from the turbulence of the wake. The dimensions of the barge, its speed of travel and the rate of discharge of waste will determine the initial dilution of waste to be expected (see Redfield and Walford, 1951).

The disposal operation should be planned so that the barge can discharge, within the limits of the disposal area, half its load on an outbound course, and half on a parallel inbound course. The two courses should be far enough apart so that the contaminated water in the two wakes are separate. The proposed disposal area is large enough so that the disposal operation could be conducted in this manner. Since the drift in the area is southerly, the return course of the barge should generally be to the north of the outbound course.

The operation should be planned so that the course can be selected to suit the conditions of wind and sea at the

time of discharge. Although the proposed disposal area is not large enough to allow complete latitude in choice of course, operations can probably be conducted satisfactorily under most conditions except for strong east to northeast winds. Under these conditions, probably no area off Delaware Bay would be completely satisfactory.

Proposed disposal area

The most favorable area for disposal of industrial wastes originating in the Delaware valley is indicated in Figure 11. This area is bounded on the northeast by a line extending southeast or 135° true from Overfalls Lightship; on the northwest by an arc lying five nautical miles from Overfalls Lightship; on the west by the outer limit of a danger area lying off Rehoboth Bay; on the south by the northern limit of a second danger area lying to the south of Indian River Inlet. These danger areas are shown on navigation charts and are subject to periodic firing practice, during which all ships are excluded.

A permissive area, lying just to the north of the proposed area is also shown. It seems likely that the drifts in this area would generally carry the wastes away from Delaware Bay, but the evidence is less positive.

The area north of these proposed disposal areas appears to be a region of uncertain drifts. The circulation is variable and might permit the temporary accumulation of successive discharges into the same mass of water. From this area it is

possible that contaminated water would move into Delaware Bay or reach the beaches of New Jersey.

The above recommendations are based specifically on the following considerations. On the basis of drift bottle returns the line extending southeast from Overfalls Lightship was found to separate a southern region where practically all bottles drifted to the south before recovery, from a northern area where substantial proportions of the drift bottles moved northward, and a few entered Delaware Bay. The salinity distributions and the escape of drift bottles from Delaware Bay indicate that the freshened water leaves through the southern part of the mouth of the estuary, and most of it flows southerly along the coast of Delaware. The transport calculated from the distribution of fresh water indicated that between 1/3 and 1/2 of the fresh water escaped to the northward.

The drift bottle returns also indicated that recoveries decreased greatly with distance from shore. It thus appears undesirable to discharge wastes in any area within five miles of shore. This minimizes the possibility of contaminated water reaching the beaches until it has drifted great distances, in which case it should become thoroughly diluted. The distance of five miles from Overfalls Lightship is specified to avoid possible movement of contaminated water into Delaware Bay by direct tidal action.

The depth of water in these disposal areas is adequate

so that the waste will be widely dispersed or greatly diluted before reaching the bottom. This minimizes possible damage to marine life in the bottom populations. As shown by the chart, Figure 11, the Proposed Disposal Area has the deepest water available immediately off Delaware Bay. The depths range from about 60 to over 100 feet. In the Permissive Area the water is shallower, but generally exceeds 50 feet in depth.

The circulation in these areas is rapid so that the contaminated water will be carried away completely and cumulative effects of successive discharges will be negligible. It has been shown that a time of only two weeks to one month is required to flush areas of nearly 2000 square miles off the mouth of Delaware Bay. The proposed disposal site occupies a small part of the area shown to have a flushing time of about 5 - 7 days. (Cf Table VIII, area 3; Table IX, area 5). Excessive accumulations of waste should not be encountered in an area where the circulation is so rapid.

The selection of a disposal area should be governed not only by hydrographic considerations but by the competing uses to which the waters are put. In the case of soluble or suspended wastes, the menace to recreastional values along shores and beaches decreases rapidly with dilution and any location more than five miles from shore is probably unobjectionable. Principal opposition to offshore disposal will probably come from fishing interests. Although the studies

made of The National Lead Company's barging operations indicated that actual damage to marine life in the area of disposal is negligible, fishermen will make very real objection to any operation in the areas they frequent. It would be desirable to move the disposal area north and east into the Permissive Area shown in Figure 11, provided this would minimize the objection of fishing interests.

It is recommended, in case offshore disposal operations are to be initiated,that a more detailed study by means of drift bottles be made in the areas of disposal under consideration. When disposal is actually commenced a program of periodic monitoring of the operation should be undertaken to check any observable chemical or biological effects which may result. This is desirable in order to meet the objections of fishing or other interests which are likely to arise.

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Table I

Drainage areas and gaged river flow of various streams tributary to Delaware River and Bay, having drainage areas greater than 50 square miles.

River or Stream	Drainage Area sq. miles	Average discharge ft^3/sec	Average discharge ft^3/sec/sq. mi.
Delaware at Trenton	6780	11,710	1.73
Crosswicks Creek	84	152	1.82
Neshminy	210	265	1.26
Rancocos, N. Branch	111	162	1.46
Schuylkill - At Phila.	1893	2,715	1.44
Chester Creek	61	78	1.27
Brandywine Creek	287	378	1.32
White Clay Creek	88	119	1.36
Maurice River	113	176	1.56
Total gaged(69.25%)	9627	15,755	1.64
Ungaged area(30.75%)	4273	7,010*	(1.64)
Total Drainage area	13900	22,765	(1.64)

*Ungaged area times 1.64 (average ft^3/sec/sq.mi.)

Table II

Distribution of fresh water in various regions of the Continental Shelf between Cape Cod and Chesapeake Bay. April, May, June observations.*

	Depth Range Fathoms	Region A	B	C	D	E	F	Totals
Total Volume 10^{10} ft^3	0-20	114	376	513	403	412	498	2316
	20-30	363	981	509	613	360	220	3046
	30-40	869	964	715	407	378	98	3431
	40-50	643	740	292	248	103	157	2183
	50-100	1170	954	648	423	621	205	4021
	100-1000	8244	10386	8000	7151	17433	7038	58252
	Total	11403	14401	10677	9245	19307	8216	73249
Volume Fresh 10^{10} ft^3	0-20	9.1	31.6	35.7	29.7	26.3	30.2	162.6
	20-30	26.2	66.4	30.1	34.4	18.1	9.1	184.3
	30-40	53.1	54.7	32.9	16.9	12.4	2.2	172.3
	40-50	32.8	35.5	11.2	7.3	2.1	1.9	90.6
	50-100	27.6	19.4	12.6	6.5	7.6	1.9	75.6
	100-1000	16.8	15.3	18.8	31.2	77.1	31.1	190.3
	Total	165.6	222.7	141.3	126.0	143.6	76.4	875.6
% Fresh	0-20	7.98	8.40	6.96	7.37	6.38	6.06	7.02
	20-30	7.22	6.77	5.91	5.61	5.03	4.15	6.05
	30-40	6.11	5.67	4.60	4.15	3.28	2.24	5.02
	40-50	5.10	4.80	3.84	2.94	2.04	1.21	4.15
	50-100	2.36	2.03	1.94	1.54	1.22	0.93	1.88
	100-1000	0.20	0.15	0.24	0.44	0.44	0.44	0.33
	Total	1.45	1.55	1.32	1.36	0.74	0.93	1.20

*Based on data from 328 hydrographic stations.

Table III

Distribution of fresh water in various regions of the Continental Shelf between Cape Cod and Chesapeake Bay. July, August, and September observations.*

	Depth Range Fathoms	Region A	B	C	D'	E'	Totals
Total Volume 10^{10} ft^3	0-20	114	376	513	611	702	2316
	20-30	363	981	509	834	359	3046
	30-40	869	964	715	616	267	3431
	40-50	643	740	292	311	197	2183
	50-100	1170	954	648	725	527	4021
	100-1000	8244	10386	8000	16781	14841	58252
	Total	**11403**	**14401**	**10877**	**19677**	**16893**	**73249**
Volume Fresh 10^{10} ft^3	0-20	9.6	32.8	47.0	46.7	46.0	182.1
	20-30	26.0	78.1	40.1	59.7	22.7	226.6
	30-40	54.2	65.3	47.8	42.6	16.9	226.8
	40-50	34.3	41.9	16.1	16.8	11.5	120.6
	50-100	35.9	31.2	22.6	25.3	16.5	131.5
	100-1000	31.8	40.1	35.6	58.8	37.5	203.8
	Total	**191.8**	**289.3**	**209.2**	**246.9**	**151.1**	**1091.4**
% Fresh	0-20	8.40	8.73	9.17	7.64	6.55	7.86
	20-30	7.17	7.96	7.87	7.16	6.31	7.44
	30-40	6.24	6.78	6.69	6.92	6.32	6.61
	40-50	5.34	5.66	5.52	5.39	5.84	5.52
	50-100	3.07	3.27	3.50	3.49	3.14	3.27
	100-1000	0.38	0.39	0.45	0.35	0.25	0.41
	Mean	**1.68**	**2.00**	**1.96**	**1.24**	**0.89**	**1.49**

* Based on data from 203 hydrographic station.

Table IV

Distribution of fresh water in various regions of the Continental Shelf between Cape Cod and Chesapeake Bay. October - March, inc. observations*.

	Depth Range Fathoms	Region A	B	C	D	E	F	Totals
Total Volume 10^{10} ft^3	0-20	114	376	513	403	412	498	2316
	20-30	363	981	509	613	360	220	3046
	30-40	869	964	715	407	378	98	3431
	40-50	643	740	292	248	103	157	2183
	50-100	1170	954	648	423	621	205	4021
	100-1000	8244	10386	8000	7151	17433	7038	58252
	Total	11403	14401	10677	9245	19307	8216	73249
Volume Fresh 10^{10} ft^3	0-20	9.5	29.7	35.8	27.2	24.4	29.9	156.5
	20-30	23.8	65.0	33.7	36.8	17.9	10.4	187.6
	30-40	45.5	50.3	42.0	21.9	15.2	3.2	178.1
	40-50	27.8	27.8	12.5	12.4	4.2	4.5	89.2
	50-100	22.7	15.4	12.0	10.8	16.4	4.1	81.4
	100-1000	41.3	25.9	19.9	21.7	36.4	14.7	159.9
	Total	170.6	214.1	155.9	130.8	114.5	66.8	852.7
% Fresh	0-20	8.33	7.90	6.97	6.77	5.93	6.00	6.75
	20-30	6.55	6.63	6.61	6.00	4.96	4.73	6.16
	30-40	5.24	5.22	5.88	5.39	4.03	3.30	5.19
	40-50	4.32	3.76	4.27	5.00	4.12	2.86	4.08
	50-100	1.94	1.62	1.85	2.56	2.65	1.99	2.02
	100-1000	0.50	0.25	0.25	0.30	0.21	0.21	0.27
	Mean	1.50	1.49	1.46	1.41	0.59	0.81	1.16

* Based on data from 325 hydrographic stations.

Table V

Summary of the Volumes of Fresh Water on the Continental Shelf between Cape Cod and Chesapeake Bay.

Depth Range Fathoms	Volumes of Fresh Water (10^{10} ft^3) Spring[1]	Summer[2]	Winter[3]
0-20	162.6	182.1	156.5
20-30	184.3	226.6	187.6
30-40	172.2	226.8	178.1
40-50	90.6	120.6	89.2
50-100	75.6	131.5	81.4
100-1000	190.3	203.8	159.9
Total	875.6	1090.4	852.7

[1]April, May, June
[2]July, August, September
[3]October to March, inclusive

Table VI

Transport across various cross sections (shown in Figure 9) near the approaches to Delaware Bay. October - November, 1951.

Area No.	Boundary	Area Fresh $10^4 ft^2$	Area Freshened $10^4 ft^2$	Increment $10^9 ft^3/day$	NTD ft/day	Transport* Fresh $10^9 ft^3/day$	Transport* Total $10^9 ft^3/day$
1	South	10.75	451			0.50	20.8
	East	6.47	327			0.30	15.0
	North	6.10	165			(0.28)	(7.6)
	Total	23.32	943	1.08	4640	1.08	43.4
2&3	South	16.61	502			0.55	16.5
	East	0.86	254			0.03	8.4
	North	6.78	408			0.22	(13.4)
	Total	24.25	1164	0.80	3290	0.80	38.4
4&5	South	10.15	387			0.565	21.5
	East	0	0			0	0
	North	0.27	64			(0.015)	(3.5)
	Total	10.42	451	0.58	5550	0.580	25.0
6	South	6.04	616			0.565	57.5
	East	0	0			0	0
	Total	6.04	616	0.565	9350	0.565	57.5
7	South	7.69	742			0.565	54.5
	East	0	0			0	0
	Total	7.69	742	0.565	7350	0.565	54.5

* The numbers in parentheses indicate the volumes of water which escape northward out of the surveyed area.

Table VII

Transport across various cross sections (shown in Figure 9) near the approaches to Delaware Bay. February - March, 1952.

Area No.	Boundary	Area Fresh $10^4 ft^2$	Area Freshened $10^4 ft^2$	Increment Fresh $10^9 ft^3/day$	Flow ft/day	Transport* Fresh $10^9 ft^3/day$	Transport* Total $10^9 ft^3/day$
1	South	24.23	338			2.22	30.9
	East	4.97	157.8			.45	14.4
	Total	29.20	770.8	2.67	9150	2.67	45.3
2&3	South	22.17	419			2.11	40.0
	East	4.88	262			0.47	25.0
	North	0.96	24			(0.09)	(2.3)
	Total	28.01	705	2.67	9550	2.67	67.3
4&5	South	15.52	298			1.69	32.4
	East	0	0			0	0
	North	8.19	355			(0.89)	(38.6)
	Total	23.71	653	2.58	10900	2.58	71.0
6	South	12.99	321			1.69	41.9
	East	0	0			0	0
	North	0	0			0	0
	Total	12.99	321	1.69	13000	1.69	41.9
7	South	11.78	256			1.69	36.8
	East	0	0			0	0
	Total	11.78	256	1.69	14350	1.69	36.8

* The numbers in parentheses indicate the volumes of water which escape northward out of the surveyed area.

Table VIII

Accumulation of River Water and Flushing Times of Various Areas (see Figure 9) in the Approaches to Delaware Bay in October - November, 1951.

River Flow = 1.08×10^9 ft^3/day.

Area No.	Surface Area $10^8 ft^2$	Volume $10^9 ft^3$	Volume Fresh $10^9 ft^3$	Mean Fresh %	Flushing Time Days
1	42	168	5.00	2.97	4.63
2	51	341	3.12	0.92	2.89
3	80	528	7.90	1.50	7.31
4	80	864	0.36	0.04	0.33
5	143	1217	10.80	0.89	10.00
6	84	716	3.46	0.484	3.20
7	229	2150	7.75	0.360	7.18
Totals	709	5984	38.39	0.642	35.54

Total Area = 1920 square nautical miles

Table IX

Accumulation of River Water and Flushing Times of Various Areas (see Figure 9) in the Approaches to Delaware Bay in February and March, 1952.

River Flow = $2.67 \times 10^9 \times ft^3$/day.

Area No.	Surface Area $10^8 ft^2$	Volume $10^9 ft^3$	Volume Fresh $10^9 ft^3$	Mean Fresh %	Flushing Time Days
1	7.5	28	1.32	4.77	0.50
2	44.0	198	3.34	1.74	1.25
3	34.0	190	7.52	3.95	2.82
4	47.0	250	3.65	1.46	1.37
5	93.0	660	13.00	1.97	4.86
6	125.0	1194	6.40	0.54	2.40
7	191.0	2150	7.93	0.37	2.97
Totals	668.0	5942	43.16	0.73	16.17

Total Area = 1805 square nautical miles

Table X

Summary of available drift bottle releases and returns for the coastal waters between 39°35'N. and 37°30'N.

Date of Release	No. of Stations	Number Released	Number Recovered	Per cent Recovered
May 10-19, 1951	51	612	91	14.9
Feb. 21-Mar. 15, 1952	74	858	11	1.3
May 13,24, 1952	59	612	52	8.5
July 17-28, 1952	90	1079	67	6.2
Totals	274	3161	221	7.0

Table XI

Number and per cent of drift bottles reaching shore when released at different distances from shore.

Miles From Shore	Number Released	Number Recovered	Per cent Recovered
0 - 5	611	91	14.9
5 - 10	654	70	10.6
10 - 15	498	33	6.6
15 - 20	306	11	3.5
Over 20	1092	16	1.5
Totals	3161	221	7.0

Table XII

Number and per cent of drift bottles recovered at various angles of departure from a course parallel to the shore.

Angle of Departure	Number Recovered	Per cent Recovered
0 - 10	105	47.5
10 - 20	34	15.4
20 - 30	9	4.1
30 - 40	14	6.3
40 - 50	11	5.0
50 - 60	14	6.3
60 - 90	9	4.1
90 -180	25	11.3
Totals	221	100.0

Table XIII

Volumes of water available daily for the dilution of introduced pollution at various locations within Delaware Bay.

Location	Channel* Stations	Diluting Volumes ($10^9 ft^3$/day) for Low Flow	High Flow
Wilmington	200	0.8	2.9
Smyrna River	300	1.6	3.1
Elbow Cross Ledge	400	3.3	4.8
Brandywine Shoal	500	10.0	12.7
Mouth	550	15.0	24.4

* Stations 1000 feet apart in mid-channel.

Table XIV

Drift Bottles Released and Returned in Delaware Bay.

Date 1952	No. Stations	No. Bottles Released	Number of Returns Total	Bay	Outer Coast
Feb.-Mar.	9	108	22	16	6
May	1	12	1	0	1
July-Aug.	52	318	96	45	51
Totals	62	438	119	61	58
Per Cent		100	27	14	13

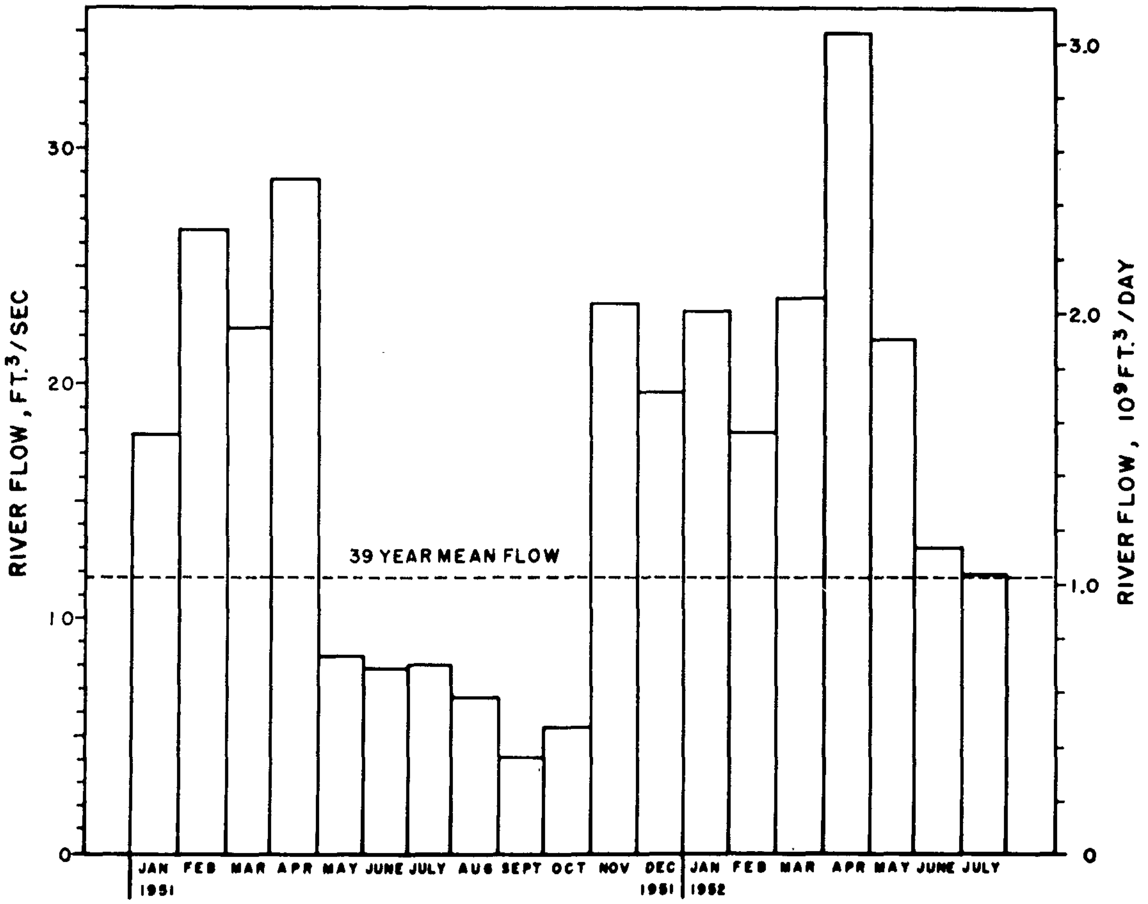

Figure 1. The monthly average Delaware River flow as gaged at Trenton for the period January 1951 to July 1952.

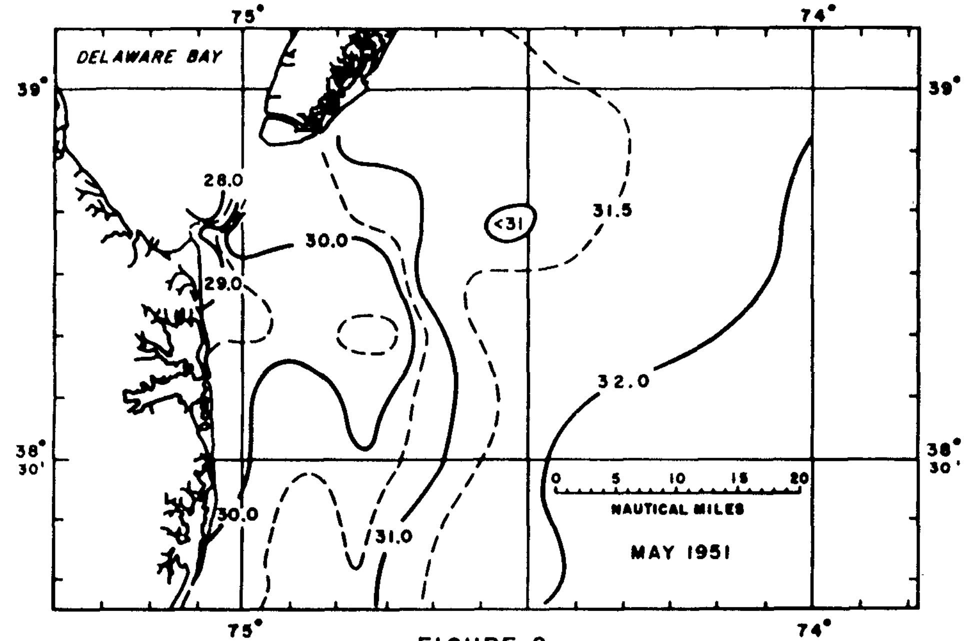

FIGURE 2

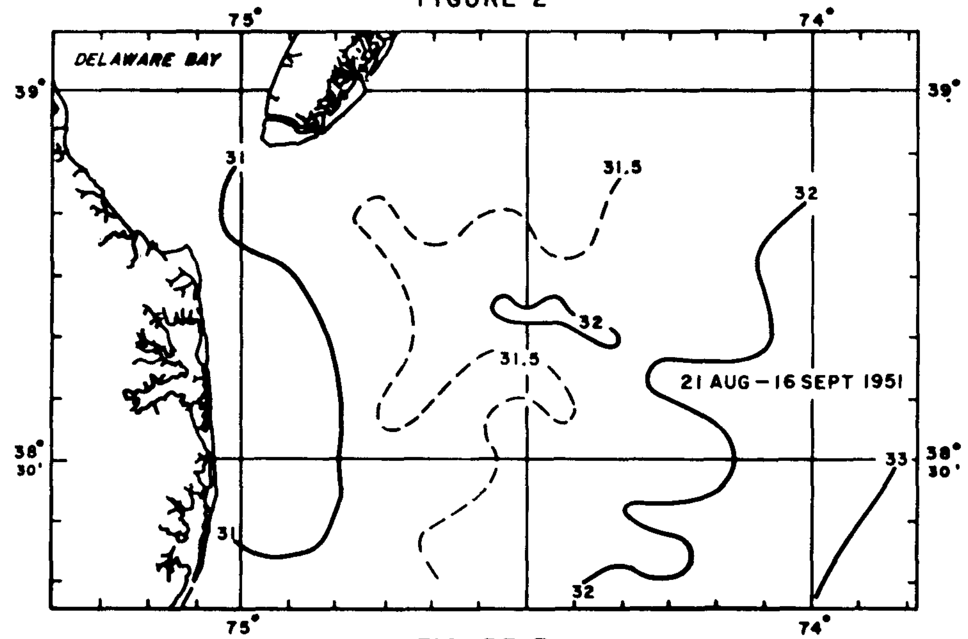

FIGURE 3

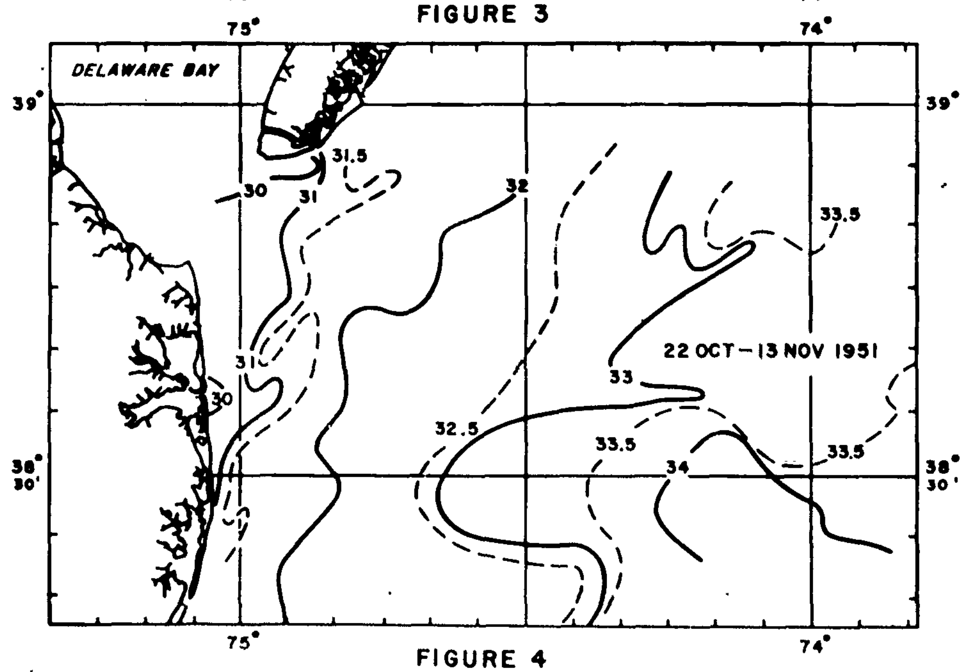

FIGURE 4

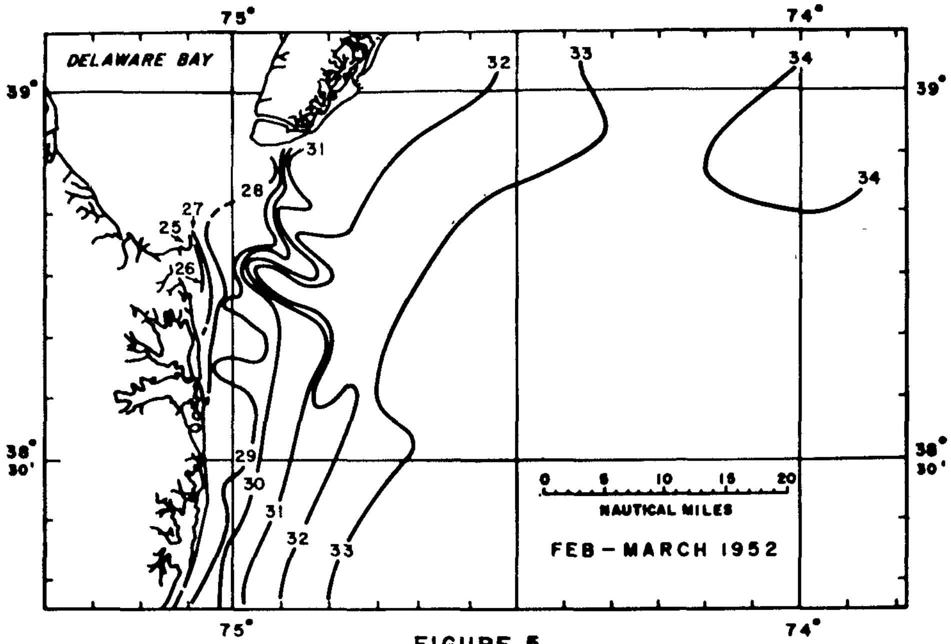

FIGURE 5

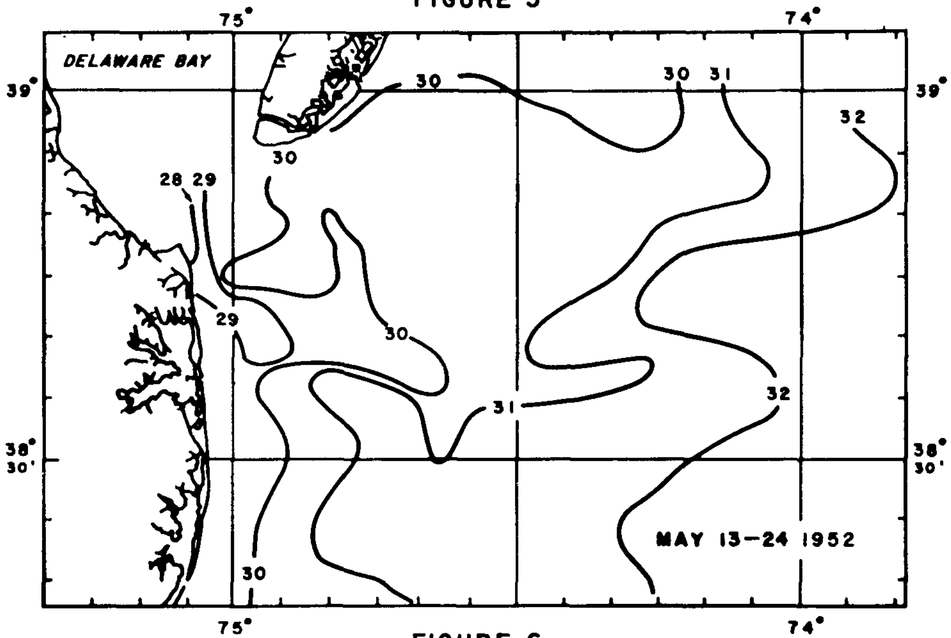

FIGURE 6

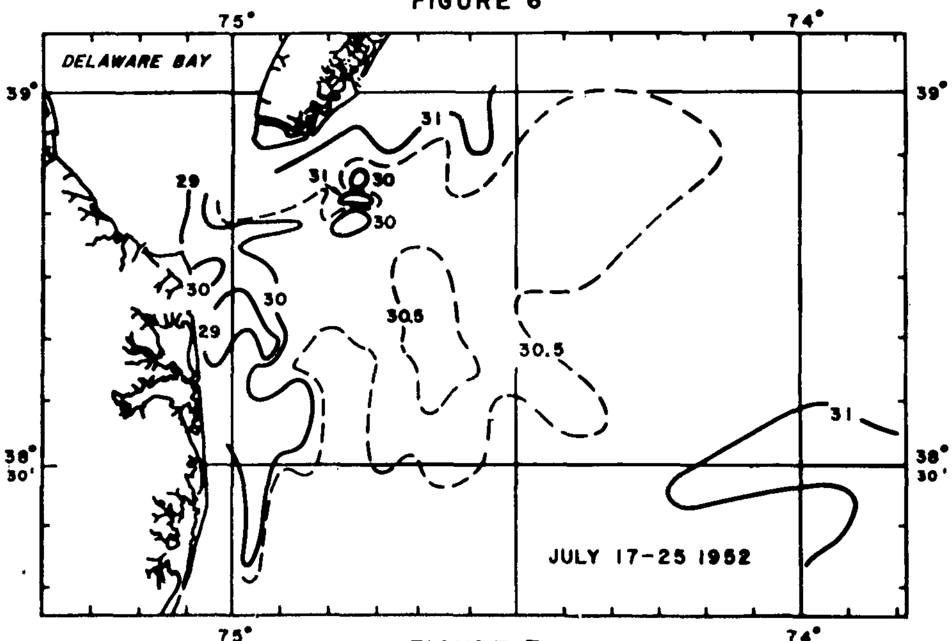

FIGURE 7

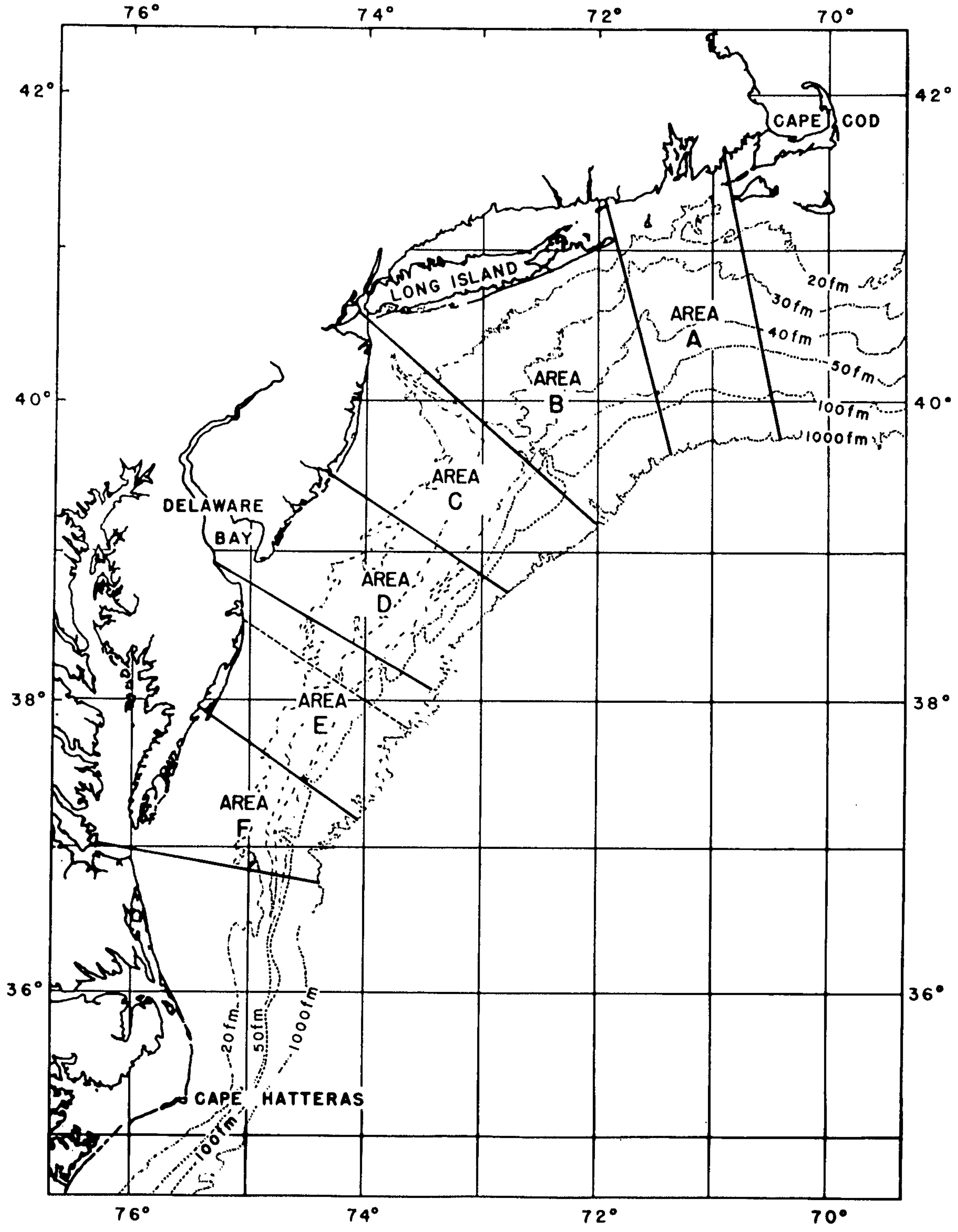

Figure 8. Regions off the Continental Shelf for which flushing times have been computed. The dashed line in area E shows the southern limit of area D' and the northern limit of area E' used for the summer observations (see Table III).

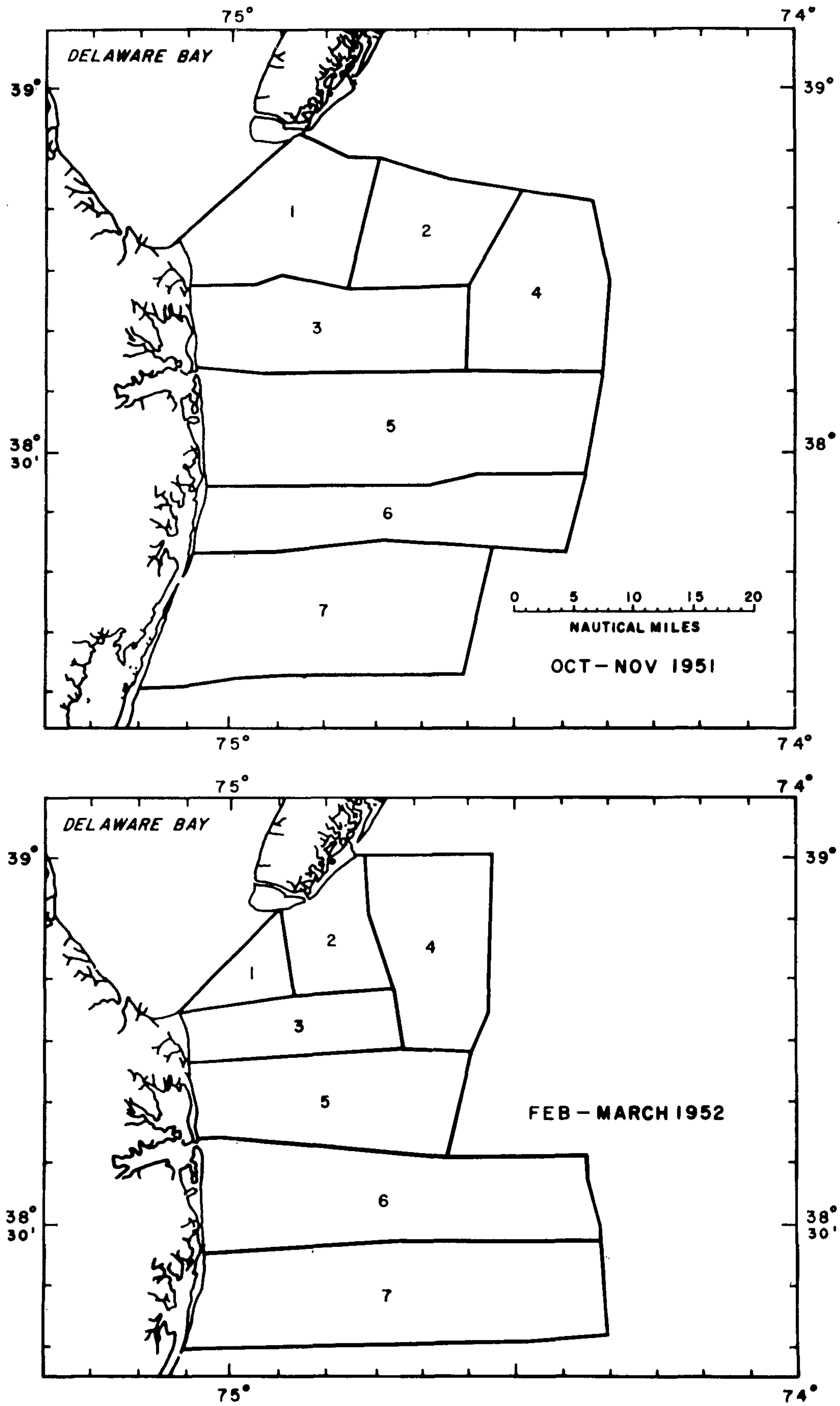

Figure 9. Cross sections and areas for which non-tidal drifts and flushing times have been calculated. Upper figure: survey of October - November 1951. Lower figure: survey of February - March 1952.

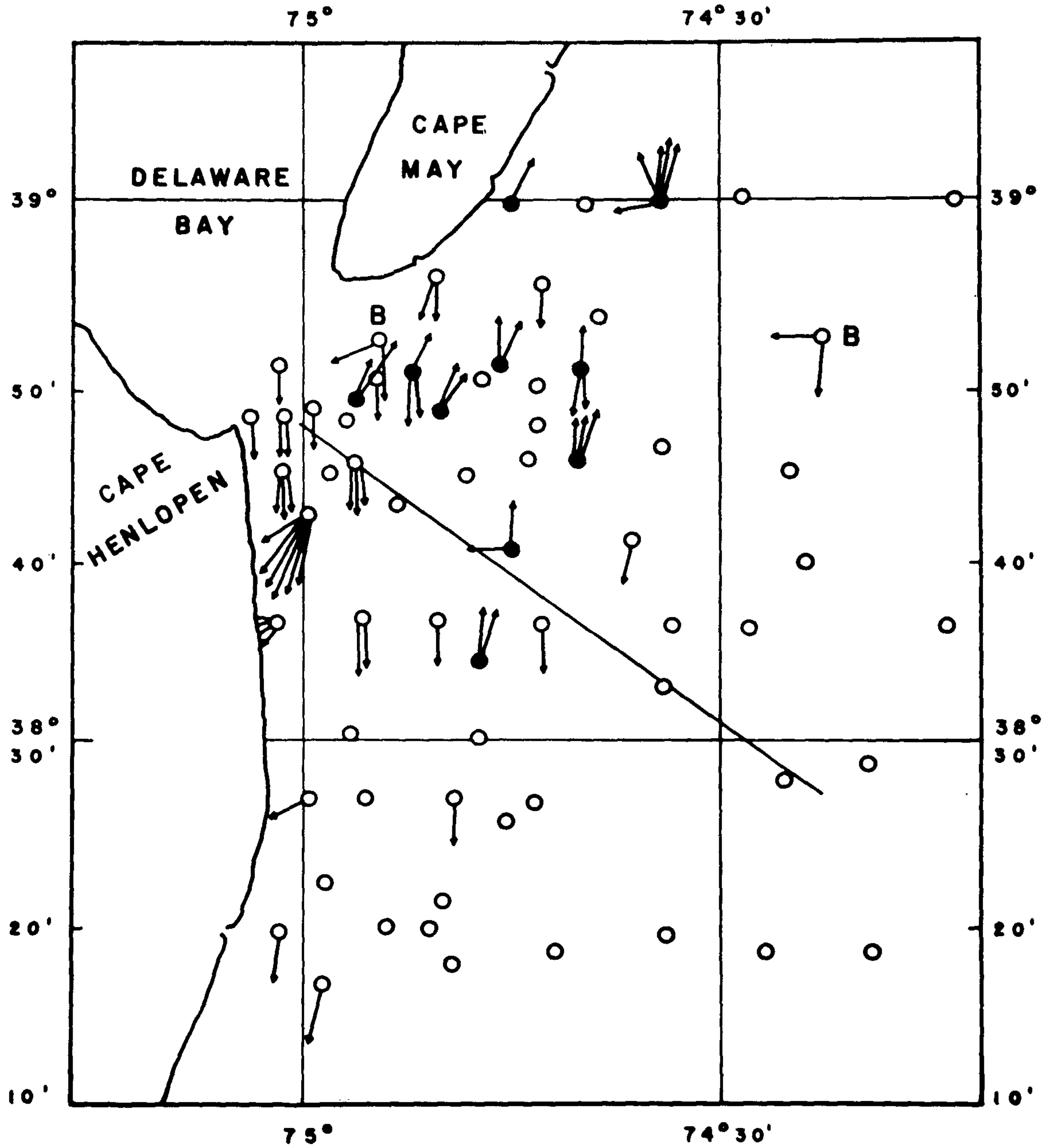

Figure 10. Locations of release of drift bottles during July 1952, and the direction of drift of the bottles prior to recovery. Bottles from the locations marked B were recovered within Delaware Bay.

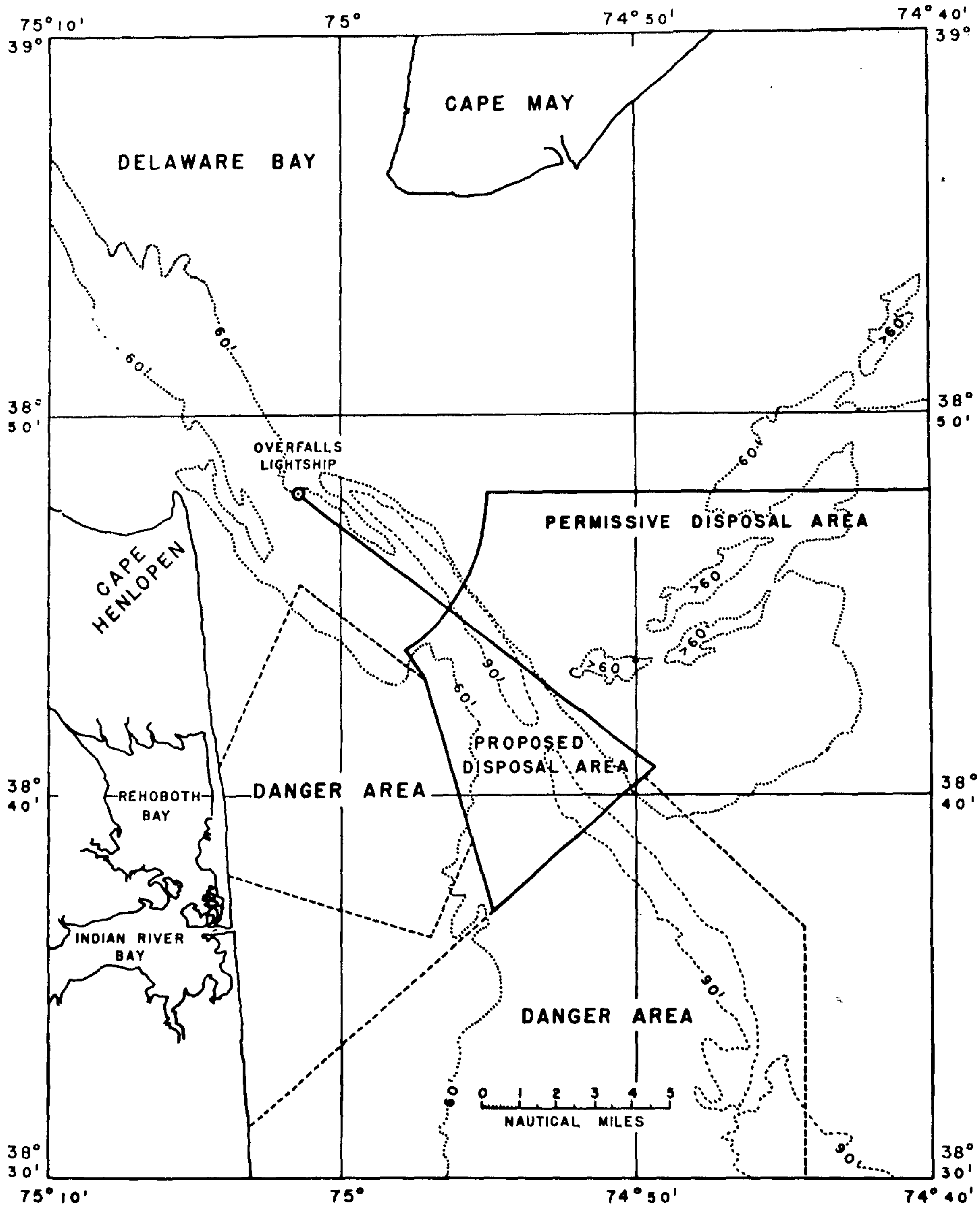

Figure 11. Areas where waste materials will have greatest possibility of wide dispersal and transport away from Delaware Bay.